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Columbia University
PALISADES, NEW YORK

Lamont Geological Observatory

Technical Report on Seismology

No. 15

Two Slow Surface Waves Across North America

Lamont Geological Observatory
(Columbia University)
Palisades, New York

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by

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ABSTRACT

Surface shear waves (Lg) with initial period about 1/2 to 6 sec with sharp commencements and amplitudes larger than any conventional phase have been recorded for continental paths at distances up to 6000 km. These waves have a group velocity of 3.51 ± .07 km/sec and for distances greater than 20° they have reverse dispersion. For distances less than about 10° the periods shorten and Lg merges into the recognized near-earthquake phase Sg.

An additional large amplitude phase in which the orbital motion of the particle is retrograde elliptical and the velocity is 3.05 ± .07 km/sec has also been observed for continental paths.

It is believed that these phases are propagated through a wave guide formed by a superficial sialic layer. The problem of explaining the propagation of these surface waves is that of finding a crustal structure which is consistent with the other data of geology and geophysics and which will provide a suitable wave guide for the new phases. A possible nature of the wave guide is described.

INTRODUCTION

Large surface waves with velocities between 3 and 3.5 km/sec from shocks on the California coast were observed at Palisades shortly after the seismographs were installed. Shocks as small as magnitude 4.7 produced sharp phases giving consistent readings to within a few seconds at distances of about 35°. Some of the shocks arrived on an azimuth of almost due west, and as three components of motion were measured with seismographs having closely similar constants, it was possible to identify two trains of waves - one exhibiting primarily SH motion, the other primarily Rayleigh type. Since the speeds were appropriate values for short period Love and Rayleigh type waves in a superficial granitic layer, the phases were called Lg and Rg. These phases were found on Palisades records for West Coast shocks from Mexico to Alaska although the separation of the later phase Rg was not clear except for those coming from nearly west.

A few records from several other stations, including Pasadena, Berkeley and St. Louis and from shocks in several regions of North America were examined for Lg. The phase was followed in to epicentral distances of a few degrees, where it became identical with Sg. It was found for every continental path examined and for no mixed path with sizeable ocean segment.

We will attempt to show that Lg consists of SH waves multiply reflected within a superficial sialic layer.

The absence of the long period branch Love waves and the duration of the wave traces cannot be accounted for on the theory of Love waves in any of the crustal structures usually assumed. The only explanation of these features which has occurred to the authors depends on the assumption that above the Mohorovicic discontinuity we have an "incompetent" layer in which the velocity of shear waves is very low.

Because of the conflict between this view and current concepts of continental structures, judgment on it is withheld until further investigations are completed.

The Lg Phase

Surface waves, for which we propose the symbol Lg, with initial period about 1/2 to 6 seconds with sharp commencements and amplitudes far larger than those of any conventional phase have been recorded on continental paths at distances up to 6000 km. These waves have a group velocity of about 3.51 ± .07 km/sec., and for distances greater than about 20° they have reverse dispersion (lower group velocities for longer periods). Typical appearance of the phase at about 4000 km is as follows (Figure 1): during the first few cycles the waves have approximately equal amplitudes on all three components, but the transverse horizontal rapidly gains amplitude and becomes several times larger than the other two within about 30 seconds. Approximately 1 minute after the commencement of the phase, the amplitude on the transverse component, having reached a value many times larger than that of S or SS on any component, begins to decrease gradually, dut does not drop to a value comparable with that of SS until about 20 minutes later, the period then being of the order 10-14 sec. The group velocity for the latter part of this phase is certainly less than about 2 km/sec, the lower limit being uncertain.

For distances less than about 10° the periods shorten and Lg merges into the recognized near-earthquake phase Sg.

The Rg Phase

The Rg phase also has large amplitudes on the seismogram. Its velocity is 3.05 ± .07 km/sec, the period of the maximum phase varies from 8 to 12 seconds. The orbital motion of a surface particle is retrograde elliptical. The dispersion is not marked but when readable it is normal (i.e. the longer periods have higher group velocities). In the neighborhood of its largest amplitude it is easily distinguished from Lg on earthquakes whose azimuth from Palisades is due west by the complete absence of correlated large amplitudes on the north-south component. Its duration is difficult to determine because its amplitude decreases to approximately that of Lg only a few minutes after the maximum. Figure 2 shows typical Rg phase recorded at Palisades. At distances less than about 10° Rg merges into the recognized surface waves of near earthquakes.

DATA

The travel time data for Lg and Rg are given in Table 1. Shocks with continental paths recorded at Palisades for which

TABLE I

No.	Recording Station	Date	Hour	Lat	Long	Magn	Δ km	Lg Travel Time sec	Lg Velocity km/sec	Rg Travel Time sec	Rg Velocity km/sec
1	Pasadena	18 Nov 29	203158	44°N	56°W	7.2	5344	1443	3.70		
2a	"	16 Aug 31	114021	30°53'N	104°11'W	6.4	1358	387	3.51		
2b	Tacubaya	"	"	"	"	"	1367	397	3.44		
2c	Ottawa	"	"	"	"	"	2944	837	3.52		
3	Charlottesville	16 Aug 31	114021	30°53'N	104°11'W	6.4	2478	725	3.42		
4	Pasadena	10 Jul 33	032204	19°N	103½°W	6¼	2222	667	3.33		
5	"	20 Nov 33	232138	73.3°N	70.7°W	7.3	5077	1448	3.51		
6	"	19 Dec 33	174830	74.0°N	70.0°W		5136	1459	3.52		
7	"	12 Mar 34	182018	41.8°N	113.0°W		962	271	3.55		
8	"	31 Aug 34	050252	73.3°N	70.7°W	6½	5077	1442	3.52		
9	"	19 Oct 35	044803	46.6°N	112°W	6¼	1478	424	3.49		
10	"	31 Oct 35	183749	46.5°N	112°W	6	1468	420	3.50		
11	"	1 Nov 35	060340	46.8°N	79.2°W		3536	1021	3.46		
12	St. Louis	13 Nov 49	195539	47.1°N	122.7°W		2783	791	3.52		
13	Palisades	1 Jan 50	025121	26°N	110°W		3700	1097	3.37		

TABLE I (cont.)

No.	Recording Station	Date	Hour	Lat	Long	Magn	Δ km	Lg Travel Time sec	Lg Velocity km/sec	Rg Travel Time sec	Rg Velocity km/sec
14	Palisades	16 Apr 50	214802	49°N	129°W		4318	1171	3.69	1391	3.10
15a	St. Louis	25 May 50	083432	$65\frac{1}{2}^\circ$N	$151\frac{1}{2}^\circ$W	6	4847	1391	3.48		
15b	Palisades	"	"	"	"	"	5369	1517	3.54	1703	3.15
16	"	5 July 50	183008	62°N	155°W		5626	1538	3.66	1781	3.16
17a	Florissant	28 Jul 50	175046	33°N	$115\frac{1}{2}^\circ$W	5.3	2343	665	3.52	790	2.97
17b	St. Louis	"	"	"	"	"	2352	651	3.61		
17c	Palisades	"	"	"	"	5.3	3756	1064	3.53		
18a	Florissant	29 Jul 50	143633	33°N	$115\frac{1}{2}^\circ$W	5.4	2343	663	3.53	783	2.99
18b	St. Louis	"	"	"	"	"	2352	661	3.56		
18c	Palisades	"	"	"	"	5.4	3756	1061	3.54	1247	3.01
19a	Fresno	1 Aug 50	083718	33°N	$115\frac{1}{2}^\circ$W	4.7	571	160	3.57		
19b	Reno	"	"	"	"	"	822	245	3.36		
19c	Palisades	"	"	"	"	"	3756	1064	3.53	1184	3.17
20	"	8 Aug 50	051200	55°N	$134\frac{1}{2}^\circ$W		4600	1283	3.59	1482	3.10
21a	St. Louis	24 Aug 50	174534	$42\frac{1}{2}^\circ$N	126°W		3026	899	3.37		
21b	Palisades	"	"	"	"		4251	1204	3.53	1419	3.00

TABLE I (cont.)

No.	Recording Station	Date	Hour	Lat	Long	Magn	Δ km	Lg Travel Time sec	Lg Velocity km/sec	Rg Travel Time sec	Rg Velocity km/sec
22	Palisades	25 Aug 50	021510	49½°N	129°W		4310	1258	3.43	1418	3.04
23	"	26 Aug 50	043927	65°N	162°W	6½	5859	1670	3.51	1859	3.15
24	"	24 Sept 50	221328	64°N	156°W		5617	1646	3.41		
25	"	28 Sept 50	214701	54½°N	134½°W		4607	1299	3.55		
26	"	3 Oct 50	090403	66°N	161°W		5777	1671	3.46		
27	"	"	124008	65½°N	128°W		4292	1201	3.57	1353	3.17
28	Tucson	23 Oct 50	161324	14½°N	92°W	7.2	2744	795	3.45		
29	St. Louis	11 Nov 50	092823	19½°N	110°W		2850	802	3.55		
30	Tucson	17 Nov 50	192818	17°N	100½°W	6 3/4-7	1989	559	3.56		
31a	Florissant	14 Dec 50	132421	40.1°N	120.2°W		2551	714	3.57		
31b	St. Louis	"	"	"	"		2566	738	3.48		
31c	Palisades	"	"	"	"		3861	1081	3.57	1269	3.04
32	"	16 Dec 50	104901	43½°N	127°W		4300	1293	3.33	1439	2.99
33a	St. Louis	3 Jan 51	122131	18°N	106°W	6¼	2754	815	3.38		
33b	Palisades	"	"	"	"	"	3980	1193	3.34	1320	3.02
34a	St. Louis	"	130424	"	"		2754	826	3.33		
34b	Palisades	"	"	"	"	6¼	3980	1202	3.31	1367	2.91

TABLE I (cont.)

No.	Recording Station	Date	Hour	Lat	Long	Magn	Δ km	Lg Travel Time sec	Lg Velocity km/sec	Rg Travel Time sec	Rg Velocity km/sec	
35a	Berkeley	24 Jan 51	071701	33°N	115 3/4°W	5 3/4	800	218	3.67			
35b	Palisades	"	"	"	"	"	3777	1069	3.53	1238	3.05	
36a	Tucson	30 Jan 51	190030	15½°N	99°W	6¼-6½	2212	620	3.57			*
36b	"	"	"	"	"	"	"	602	3.67			
37	Palisades	1 Apr 51	192110	40½°N	125°W		4236	1207	3.51			
38	"	22 Apr 51	123616	76°N	73°W		3889	1088	3.57	1289	3.02	
39a	Ottawa	20 June 51	183710	35½°N	103°W		2544	718	3.54			
39b	Palisades	"	"	"	"		2598	736	3.53			
40	"	23 June 51	033240	31½°N	113½°W		3663	1080	3.39	1222	3.00	
41	"	25 June 51	161232	61°N	150°W	6¼	5395	1513	3.57			*

* Focal depth 100 km

epicenter location and origin time are available form the basic material for this study. A few seismograms at Berkeley, Pasadena and St. Louis have been examined during brief visits to these stations, and occasional readings from other stations have been used primarily to demonstrate that the Palisades results are typical. Figure 3 shows the paths of Lg for these earthquakes

Although the instrumentation at Palisades has increased considerably beyond that available for our earlier recordings, the first instruments installed here were quite good for this study. They provided three well matched components with good response in the period range of Lg and Rg. It is difficult to identify Rg without a vertical which matches the horizontals, and even with such instrumentation it was a great advantage in learning the distinctive features of these phases to have many of the shocks arriving from direct due west.

The readings at Pasadena were made from an excellent file of records selected several years ago by Gutenberg and Richter. This file was arranged in the order of increasing epicentral distances, and there were but few gaps of more than 1 or 2 degrees epicentral distance. Every record in this file was examined, regardless of the nature of the path. It was found that Lg was recorded only for continental paths.

It is apparent from the velocity and large amplitudes that Lg is a wave which is confined to a surface or near-surface layer by wave guide action. A rough calculation given below suggests the boundary is no deeper than the Mohorovicic discontinuity, and it is very likely to be shallower. Regardless of the details of the wave guide, no energy will be radiated into the region below the Mohorovicic discontinuity from any wave whose phase velocity is less than about 4.7 km/sec, the velocity of shear waves below this discontinuity. The problem of explaining the propagation of the surface waves reported in this paper is that of finding a crustal structure which is consistent with the other data of geology and geophysics, and which will provide a wave guide for the new phases introduced here which require group velocities of about 3.5 km/sec at periods of about 2 seconds and less than 2 km/sec at periods of about 12 seconds.

POSSIBLE NATURE OF WAVE GUIDE

In the first attempt to explain this surface wave, the authors were impressed with the similarity of its commencement with that of the compressional wave in shallow water transmission[1] (Figure 4). Lg was therefore considered to be the high frequency branch of the classical Love Wave dispersion curve in a sialic surface layer, but this hypothesis was quickly abandoned for the following reasons: (1) No trace of the long period branch of Love waves could be found; (2) the duration of the wave train, which depends upon the ratio between the short period group velocity and the minimum of group velocity, is an order of magnitude larger than

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[1] Maurice Ewing, J.L.Worzel, C. L. Pekeris, "Propogation of Sound in The Oceans", Memoir 27, Geol. Soc. Amer., 1948.

allowed by Love wave theory; (3) the motion on the other two components required some extension of the classical Love wave theory.

Alternative hypothesis allowing sufficiently low group velocities to explain the duration of the transverse motion must involve multiple reflection of SH waves in a solid surface layer at angles of incidence approaching normal. One example of this type of propagation is that of Love waves if the theory be extended to include transmissions at angles steeper than the critical angle with attendant leakage of energy into the substratum. This type of transmission has been observed for the analagous case of multiple reflected compressional waves in shallow water underlain by a smooth rock bottom, the energy loss through leakage being compensated by automatic volume control of the recording system.[2] Use of multiple detectors — the usual geophysical reflection spread — showed that the phase velocity approached infinity as the group velocity approached zero. Despite the unusually large contrast in acoustical impedance at the sea floor in this case, simple amplitude calculations indicate that without the large time increase of amplitude gain provided by use of automatic volume control this type of propagation would not have been observable.

Similar amplitude considerations in the case of the Lg phase, as well as the complete absence of a longer period branch

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2. K.E.Burg, Maurice Ewing, Frank Press, E.J. Stulken, "A Seismic Wave Guide Phenomenon", in press Geophysics.

of Love waves, seems to rule out the possibility that the layer through which Lg is propagated is underlain by a solid having a value of shear velocity anywhere near that of the layer.

A second example is the propagation of SH waves in a plate, by means of multiple internal reflections. Typical dispersion for this case is shown in Figure 5, taken from a paper of Press and Ewing[3]. According to this dispersion curve the first oscillations at a point whose distance from an implusive source is large compared to the plate thickness, travel with the velocity β, of shear waves in the plate, and have high frequencies and an impulsive beginning. The train of waves which follows is of infinite duration and decreases in frequency to a cut off value of $f = n\beta/2H$, where H is the thickness of the plate and $n = 1, 2, 3....$ is the mode of propagation. The SH waves in a plate which is in contact with a fluid substratum cannot "leak" out of the plate, even for angles of incidence approaching normal. In a general way an earth model in which a sialic plate rests on a "fluid" substratum could explain the main features of the Lg waves as observed on a transverse horizontal seismograph. For the cut-off frequency of about 1/12 cps indicated on the Palisades seismograms the plate thickness would be about 20 km for propagation in the first mode.

The theory for propagation of SV waves in a plate floating on a fluid substratum of finite thickness is more complicated, due to the transformation of part of the energy into compressional waves at each reflection, but its general features can be deduced

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[3] Frank Press and Maurice Ewing, "Propagation of Elastic Waves in a Floating Ice Sheet" in press Trans. Amer. Geophys. Union

from the work on the floating ice sheet, in which the thickness of the fluid substratum was unlimited. According to this theory there is an infinite number of modes of propagation. In the first mode a short period Rayleigh wave at speed .92β is predicted at one end of the spectrum with a longitudinal wave with velocity appropriate to the plate at the long period end. There is wave guide propagation with no leakage for the short period Rayleigh waves, but the long period longitudinal waves will suffer attenuation through radiation of energy into the fluid. In higher modes it can be shown that the first arrival of short period SV waves is simultaneous with the SH waves which initiate Lg in the above discussion.

Furthermore the impulsive, high-frequency beginning of SV waves propagated in the second mode is similar to that for SH waves, corresponding to the disturbances in the other two components as described above. If both modes are present the first motion due to SV would be high frequency waves at the velocity β on the vertical and longitudinal components showing reverse dispersion. They would be followed, at a velocity .92β by Rayleigh waves whose period corresponds to a wave length small compared to the thickness of the plate. The subsequent part of the record would consist of a mixture of the two modes, but in the case of the hypothetical earth structure added features would be introduced by the finite thickness of the liquid layer and by propagation through the underlying solid which controls the propagation of the long period Rayleigh waves.

According to this theory we might expect long longitudinal waves commencing with a velocity $.94\,\alpha$ and compressional waves of short period commencing with the velocity α, but these will be much more strongly attenuated than the Lg waves, due to larger leakage of energy through the liquid layer. Clearly the effect of viscosity also must be considered.

The numerous curious features of S are well known. A partial list includes poor transmission from shallow shocks for distances between 5° and 25°, periods so different from that of P, dependence on travel time on polarization. It is clear that a thin viscous semi-liquid layer at or above the base of the crust would strongly affect shear waves, particularly in the shorter period range. Such a layer could not readily be detected by travel time techniques, excluding those where the focal depth varies to exceed layer depth. It is mostly by surface wave studies, reflections and amplitude studies such as used by Gutenberg[4] that this layer could be detected. We believe that the evidence which led Gutenberg to propose the existence of a low velocity layer is not inconsistent with the existence of a semi-liquid layer at the base of the crust.

CONCLUSIONS

The fact that Lg is observed for continental paths only, being gradually eliminated as the ocean path increases beyond 100 km offers good support of the conclusion based on Rayleigh wave propaga-

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[4] B. Gutenberg, "Structure of the Earth's Crust in the Continents", *Science* 111: 29-30, 1950.

tion across oceans[5] and seismic refraction investigations of ocean basins[6] that the sialic layer is limited to continents only. There are many observatories so located that the occurrence of Lg on a record would be highly diagnostic for immediate epicenter location. Lg is a powerful tool for the investigation of crustal structure under small bodies of water provided paths are chosen so that lateral refraction does not introduce complications. For example, the possibility that sialic crust of continental thickness underlies the Gulf of Mexico may be quickly rejected by inspection of the Palisades records from shocks off Mexico.

The high quality of the wave guide which transmits Lg is remarkable. The efficient energy transmission from small quakes and the similarity of various North American paths except those along mountain systems means that a simple set of parameters will specify the "mean" sialic crust. This suggests that on the whole the sialic crust of the continent approximates a plate with good precision. We interpret this broadly -- roots of mountain systems and other thickness variations of limited lateral extent would not prevent transmission of Lg, although they would affect the regularity of the dispersion. On the other hand, propagation along the mountain systems of West Coast of North America alters the velocity and character of Lg.

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[5] Maurice Ewing and Frank Press, "Crustal Structure and Surface Wave Dispersion", Bull. Seism. Soc. Amer., 40: 271-280, 1950.

[6] Maurice Ewing, J. L. Worzel, J. B. Hersey, Frank Press and G. R. Hamilton, "Refraction Measurements in the Atlantic Ocean Basin, Part I.", Bull. Seism. Soc. Amer., 40: 233-242, 1950.

The apparent discrepancy between the uniform, homogeneous continental crust revealed by Lg and the highly irregular one revealed by seismic refraction measurements using explosions as sources, is probably completely explained by the difference in the wave lengths used in the two techniques.

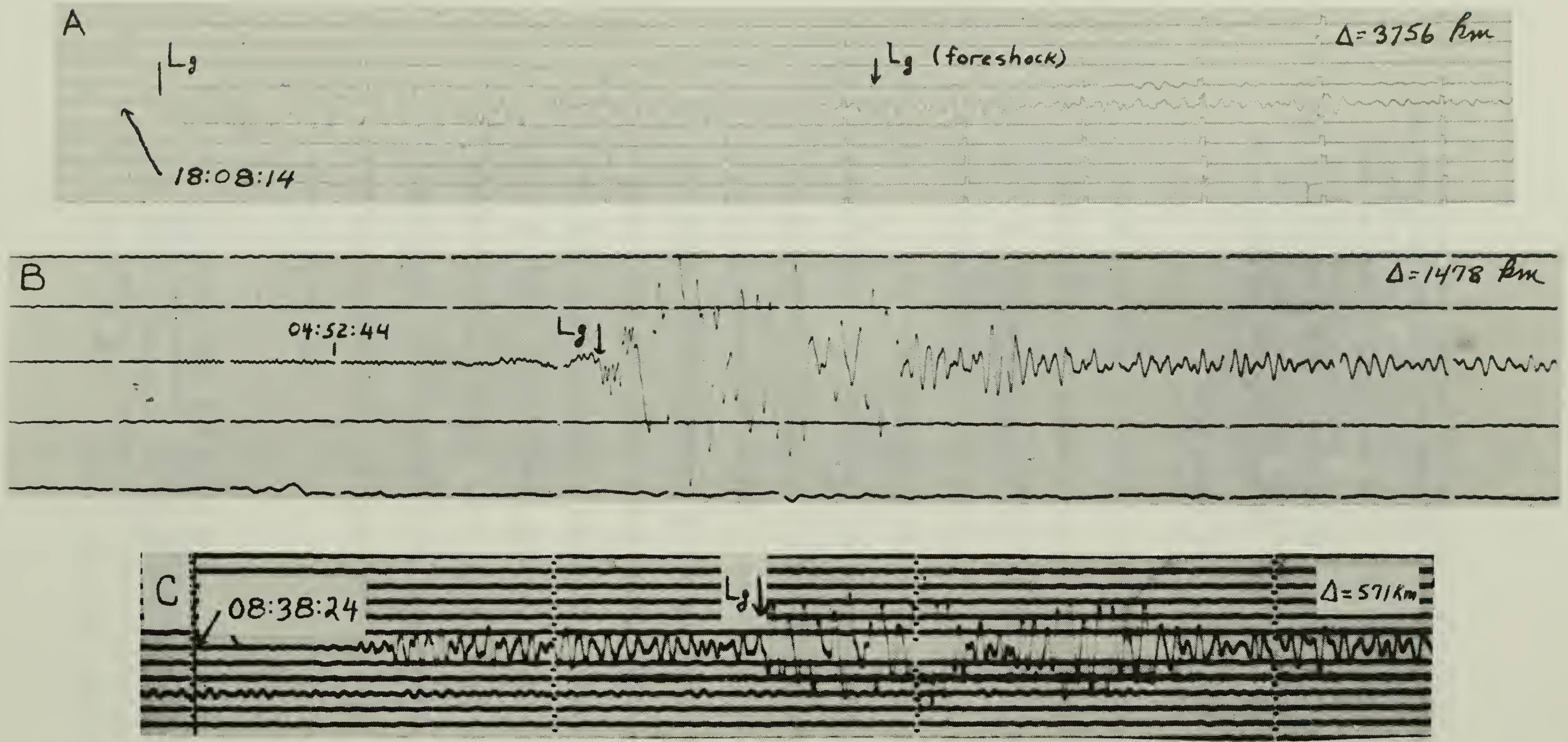

Figure 1. Typical Lg phases; A) Palisades N-S seismogram for shock 17c; B) Pasadena Linear Strain Seismogram for shock 9; C) Fresno Z seismogram for shock 19a.

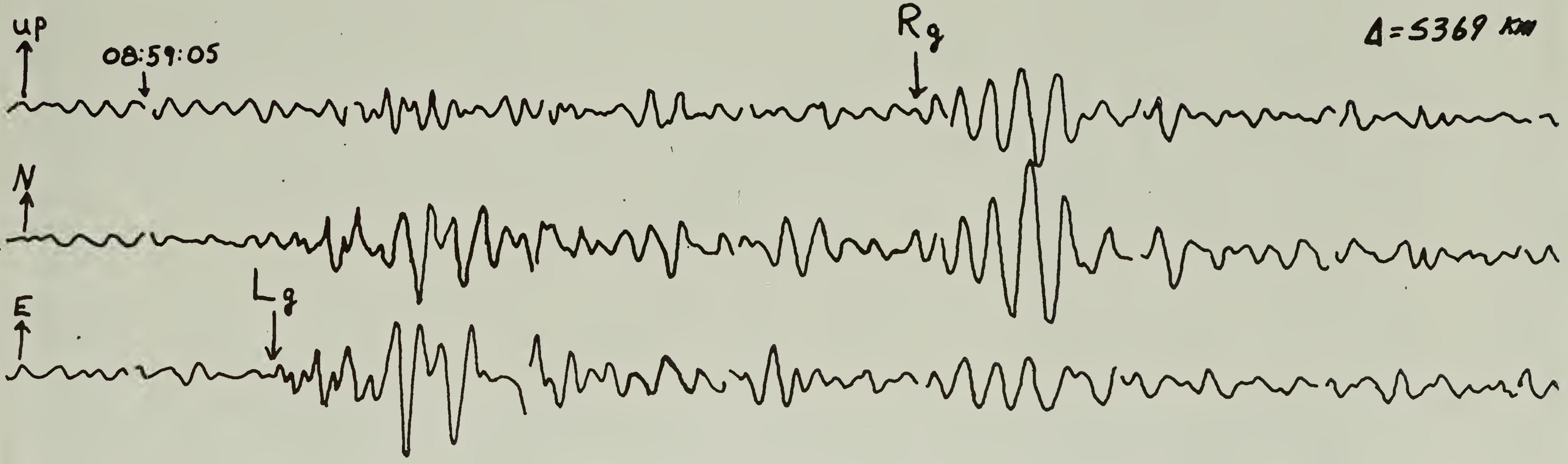

Figure 2. Palisades seismograms illustrating Lg and Rg for shock 15b.

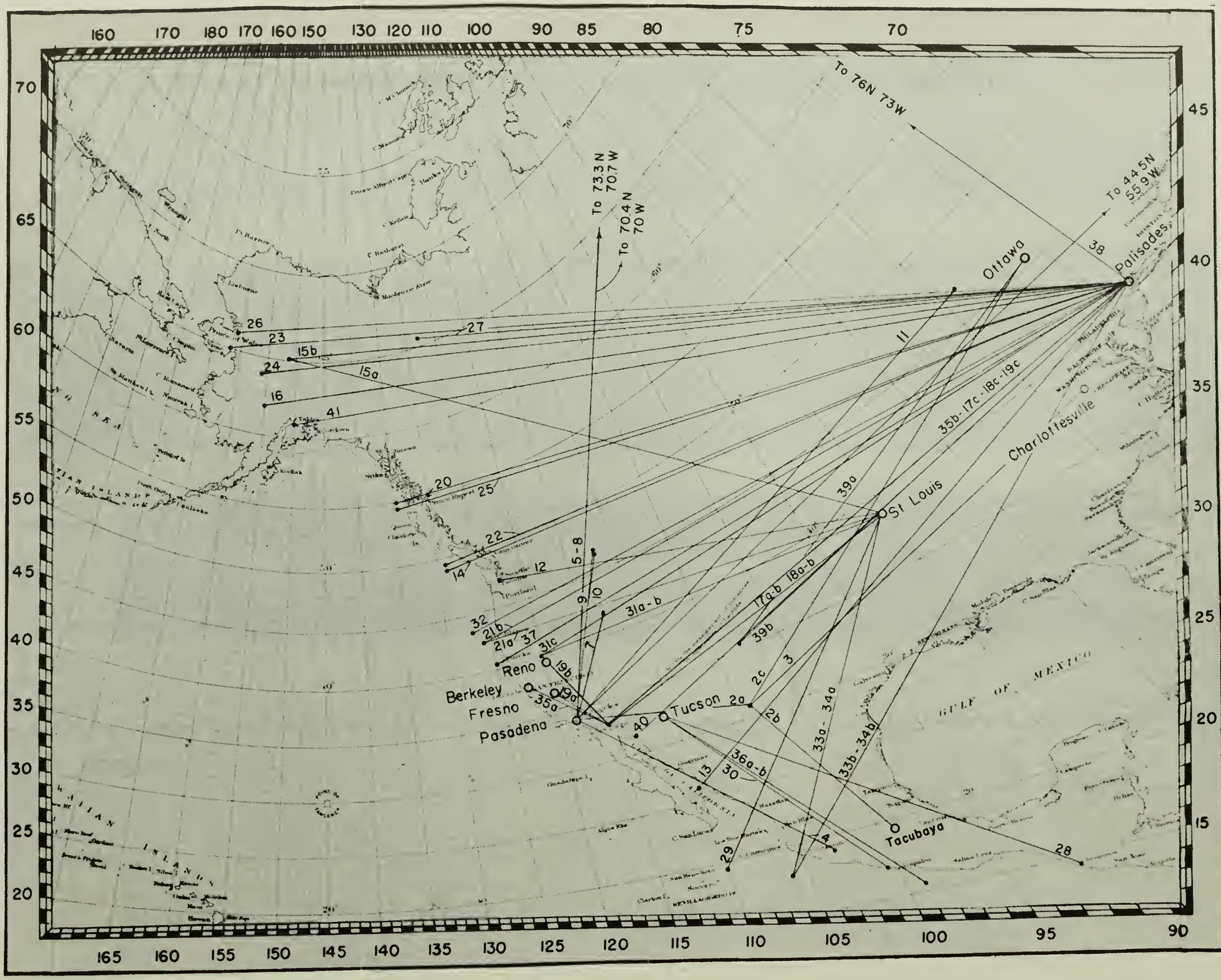

Figure 3. Paths traversed by Lg phases listed in Table 1.

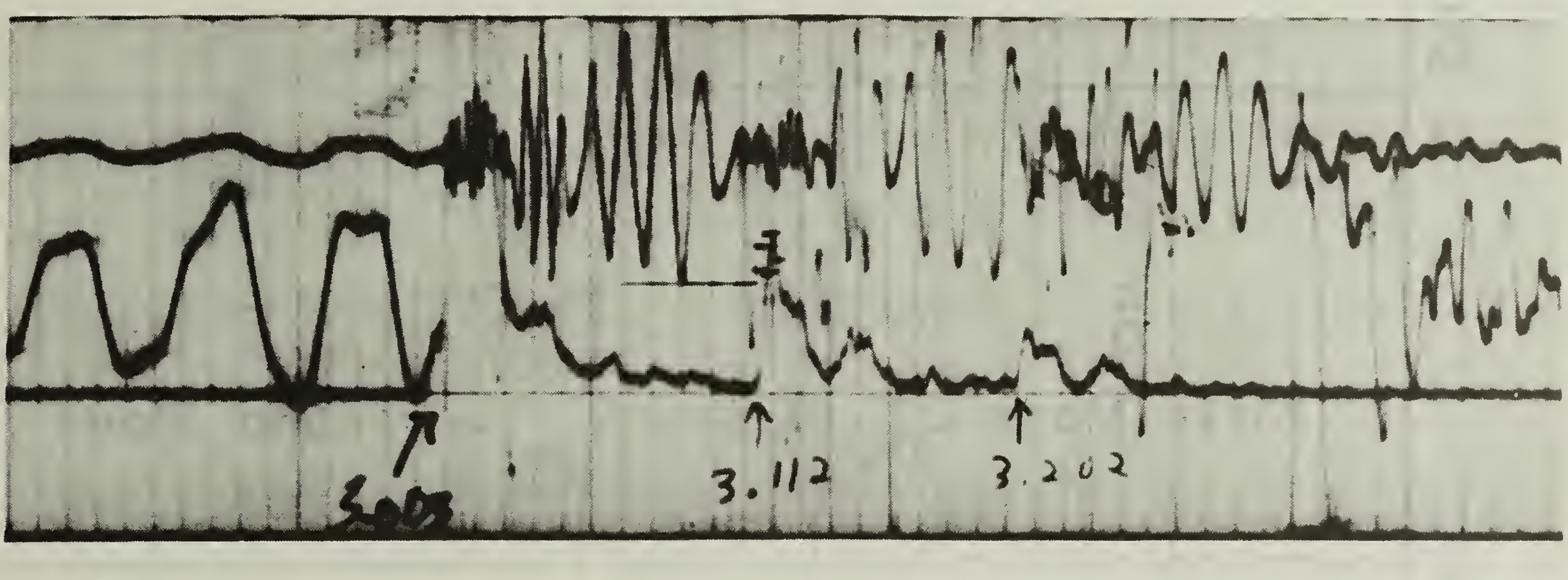

Figure 4. Typical seismogram from a shallow water shot illustrating reverse dispersion in the water wave.

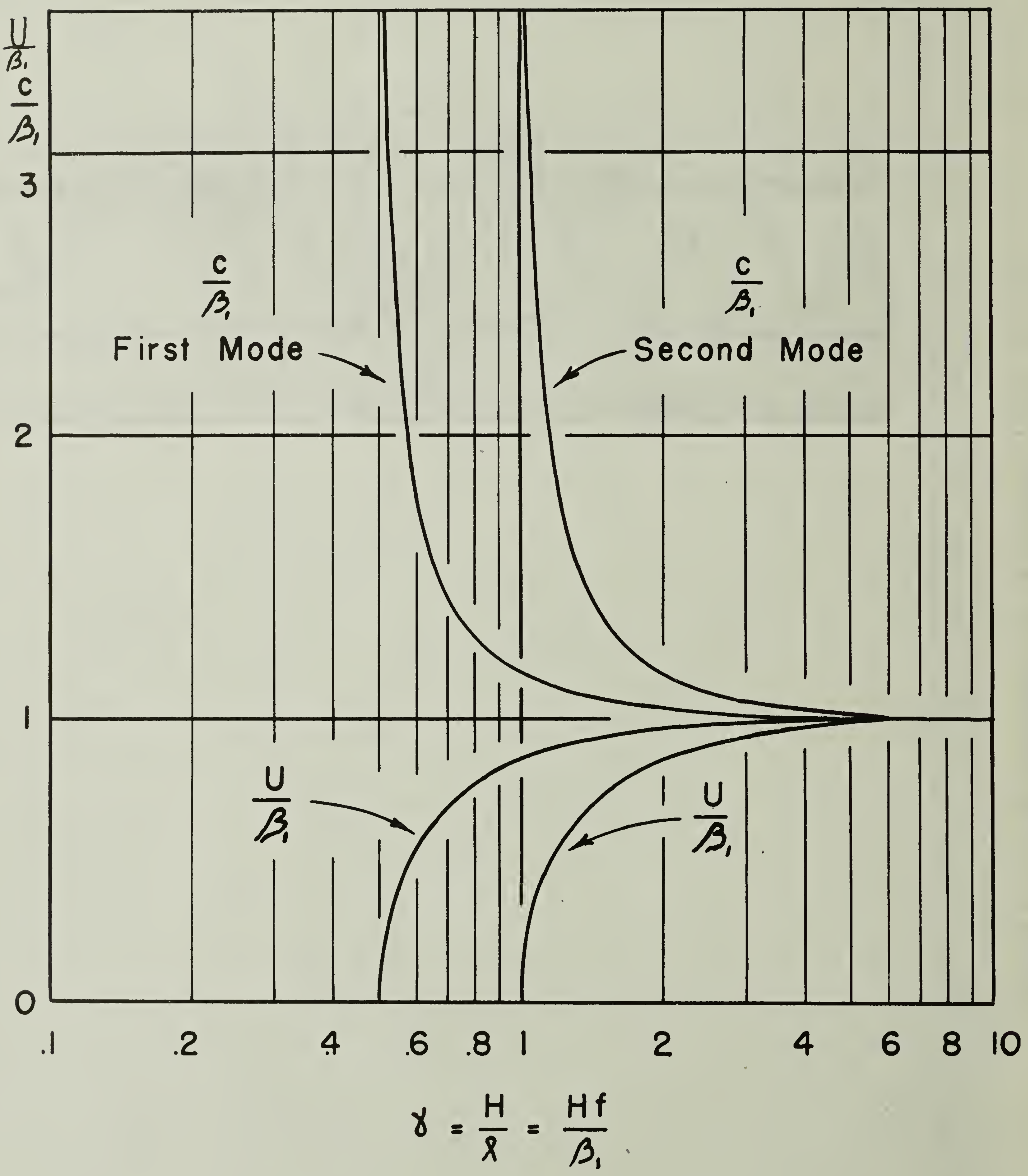

Figure 5. Dimensionless phase velocity c/β_1 and group velocity U/β_1 curves for SH waves in a plate.